Efficient Automotive Propulsion: Response to NHTSA Question 2

(Federal Register 67, no. 26, Feb 7/02, page 5771)

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Developmental Concept

I am not going to discuss revolutionary technologies like fuel-cell propulsion or hybrid propulsion (although there are two outstanding high-voltage hybrid cars sold in the US). The proposed improvements are based on evolution, not revolution, and have two advantages:

- *The technologies can be implemented in essentially all new light-duty vehicles; and*
- *the incremental manufacturing cost would be low, less than the value of the fuel savings.*

Although more than a decade would be needed to *fully* achieve these changes in a way satisfactory to all customers, substantial improvements in fuel economy could be made sooner.

Technological Goal

The goal of the proposed propulsion technologies is:

- *high efficiency in typical low-power operation, while retaining the capability for high power.*

Present automotive propulsion systems have high-power capability, but are inefficient in ordinary driving. High power driving is rare (mainly high-speed hill climbing and acceleration at high speed); almost all fuel is consumed in low-power driving. For example, high speed driving on a level road requires about 20kW for an average car, much lower power than today's engine capability of over 125kW..

Physical Concept

Today, friction is used to control the use of energy in automobiles. It is used to smoothly shift gears in automatic transmissions (with a torque converter), to regulate the flow of air into the engine (with a throttle), and to adjust the output of the air conditioner (as well as to slow the vehicle with brakes). It's analogous to dimming lights with a variable resistor. The way dimming used to be accomplished, the energy used for lighting was reduced by placing a resistor in the line, i.e. by heating the resistor. Now we dim lights by controlling the system electronically, rapidly switching the electricity on and off such that the fraction of on-time yields the desired amount of lighting. Very little energy is wasted and the switching is not noticeable.

There are two advantages to sophisticated control of automotive propulsion: Frictional losses are reduced; and the improved controls enable the efficient technologies to be designed so they are satisfactory to customers.

<u>Technologies</u>

1) The basic change is to smaller engines coupled with sophisticated transmission.

A smaller engine has less internal friction. In today's typical gasoline engines, while the work done on the pistons by the hot combustion gases is about 38% efficient at typical engine speed, the work done overcoming internal friction introduces, about another 50% efficiency factor in the Urban Driving Cycle, for an overall engine efficiency of only 0.38*0.50 = 19%. Smaller engines are more efficient because the friction is roughly proportional to displacement. There are at least three ways the system can be designed so that a small engine can still provide all the maximum power now available with a large engine: high engine-speed capability, or super/turbo charging, or, possibly, a dual or split engine on the same shaft (where an added engine-section is brought on line when needed). By the way, good fuel economy does not require high efficiency at high power.

An excellent example of an engine capable of operating at high speed is the 1.7 liter engine of the Honda Civic EX. Scaled to 2.0 liters, it would have the same power capability as a typical 3.0 liter engine, but have two-thirds as much friction in normal operation. With good design, either continuously variable transmission or motor driven gear shifting can enable rapid and controlled changes in engine speed. These technologies are now available on some production cars. With good design, the torque converter could be eliminated (with substantial energy benefit in urban driving), so that engine speed and vehicle acceleration are smoothly controlled through intelligence rather than friction. In this way, a smaller engine can be made fully satisfactory to customers even though it involves more gear shifting and higher engine speeds. Further work is needed to perfect this approach, but it involves design and refinement, engineering of the kind the industry regularly does, and does very well.

After development, such propulsion systems would cost less than what they replace.

2) Sophisticated controls and high-efficiency accessories enable turning the engine on-and-off.

With modern controls the engine can be turned off and on with almost no noise or vibration. However, enhanced electrical capability and high efficiency accessories, especially air conditioning, are needed if the engine is to be off for most of the time when the vehicle is stopped or in braking. The industry move to 42 Volts instead of 12 Volts will enable engine on-and-off capability to be achieved as a by-product. As with the engine, what is needed for air conditioning is high efficiency in normal low-demand situations, combined with the capability to handle extreme situations. Air conditioning for electric vehicles has provided some experience in this area. This improvement would increase costs, but the increase would not be large in the overall picture.

3) Weight reduction can be used to make heavier vehicles lighter to enhance safety.

Traffic safety can be greatly enhanced by systematic changes in vehicle design. One part of this safety strategy is to redesign the heaviest vehicles, decreasing their weight, while maintaining the weight of the lightest vehicles. Good options include the smaller engines and transmissions just mentioned, unibody or space frame structures (rather than the body on frame of most SUVs and pickup trucks), and increased use of light materials (high-strength steels, aluminum and engineering plastics). To make a definite projection, the average weight reduction in the calculation that follows is taken to be 10%. More than this reduction would be practical. However, it would be wise to make larger weight reductions for typical light trucks and heavier cars, and no reductions among the lightest cars. A 10% reduction in aerodynamic and tire loads is also assumed, perhaps less than might be expected normally over the next decade.

4) Sophisticated engine controls offer engine efficiency benefits

Valve controls enable decreased frictional loss in air management by substituting valve action for the throttle. (The action is closely analogous to light dimming.) This has been fully implemented in a BMW production engine. Less-ambitious variable valve timing, already implemented in several engines, improves efficiency at low and high engine speeds.

The above technologies have been grouped so they address different energy-saving opportunities. The first involves reducing engine and transmission friction; the second, turning off the engine; the third, load reduction; and the fourth, residual engine efficiency opportunities. Recovery of some braking energy with a 42-Volt system has not been included. That might be more costly to achieve than the technologies considered.

<u>Gains in Fuel Economy</u>

Consider a recent midsize sedan similar to Ford Taurus with its standard engine. First I establish a reasonable limit: the fuel economy that could be achieved strictly through propulsion system efficiency improvement – without reducing mass or tire and aerodynamic loads (Table 1). For this exercise, I assume that all engine and transmission friction is eliminated (certainly not practical), while I assume that the engine's maximum efficiency is at today's optimal of 38% and that the accessory load is reduced by one-third.

Table 1. "Test" Fuel Economies of a Recent Car, and Zero-Friction-Propulsion Car, Same Load

	Urban Driving Cycle	Highway Driving Cycle	Composite Cycle
late 1990s base car	22.2 mpg	35.3 mpg	27.0 mpg
"limit", car w/ same load	56.3 mpg	64.2 mpg	59.6 mpg

Now consider implementing the four types of technologies sequentially. (See Table 2.)

Table 2. Projected Fuel Economies from Implementing the Four Types of Technologies

	Urban Driving Cycle	Highway Driving Cycle	Composite Cycle
base car plus step (1)	29.6 mpg	42.9 mpg	34.4 mpg
w/ steps (1) and (2)	33.3 mpg	42.9 mpg	37.0 mpg
w/ steps (1), (2) and (4)	35.0 mpg	43.9 mpg	38.5 mpg
include 10% lower load	37.7 mpg	48.5 mpg	41.9 mpg

Summary of the Fuel Economy Projections

The fuel economy gain projected here is 41.9/27.0 or 55%. This corresponds to a fuel saving at the same number of miles of 27.0/41.9 of 35%. Our study of light-truck fuel economy shows larger gains than I have projected here (An, Friedman & Ross). The major point is that savings on this scale could apply to essentially all new light-duty vehicles, albeit more for heavier light trucks and less for lighter cars.

What market impediments might limit adoption of such technologies?

1) All the manufacturers are adopting some of these measures, but in today's market manufacturers tend to simultaneously increase vehicle mass and engine power. 2) Most manufacturers prefer to continue to produce vehicles like those they already produce, emphasizing changes in style rather than technology. 3) Large, heavy and expensive vehicles are the most profitable (because the market is moving to higher income buyers, and because competitors are more numerous among smaller, lower-priced vehicles). 4) The manufacturers know that buyers are interested in many vehicle attributes, and they know it's hard for buyers to select for fuel economy in those circumstances. In this market, most manufacturers only offer high fuel economy in bottom-of-the-line cars.

Finally, while these fuel economy technologies offer the same maximum-speed and acceleration-times, initial versions may have subtle disadvantages, somewhat uneven acceleration and somewhat more noise. Unless engineering efforts are made to moderate these disadvantages, the changes would not be satisfactory for some customers.

Policy.

I am not a policy specialist, but I have three general suggestions: a) We care about fuel. Let us move to express the regulation in gallons per 100 miles, analogous to European practice, instead of miles per gallon. b) Motivate reducing the weight, stiffness and frontal height of the heavier light trucks, as is strongly justified by safety. c) Strive to enable the old "Big-Three" to remain competitive. This requires pushing them strongly to be innovative, but not too hard. I think a good combination is to set ambitious goals, but to be generous with the required rate of progress, such as 12 to 15 years to achieve a one-third reduction in gallons per 100 miles (i.e. a 50% increase in fuel economy).

Citations to Our Recent Work in This Area

DeCicco, J, F An & M Ross, 2001. Technical Options for Improving the Fuel Economy of Cars and Light Trucks by 2010–2015, American Council for an Energy-Efficient Economy.

An, F, J DeCicco, & M Ross, 2001. Assessing the Fuel Economy Potential of Light-Duty Vehicles, Society of Automotive Engineers Paper No. 2001- 01-2482.

An F, D Friedman & M Ross, 2002. Fuel Economy Potential for Light-Duty Trucks, Society of Automotive Engineers Paper No. 2002-01-1900 (to be published).

M Ross & T Wenzel, 2001. Losing Weight to Save Lives: A Review of the Role of Automobile Weight & Size in Traffic Fatalities, American Council for an Energy-Efficient Economy; and An Analysis of Traffic Deaths by Vehicle Type and Model, American Council for an Energy-Efficient Economy. http://www.aceee.org/press/t021pr.htm